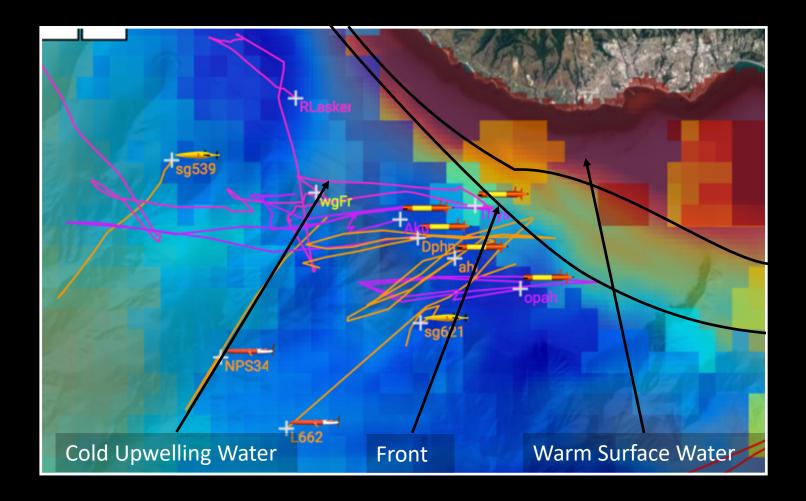


### Outline

- Motivation
- Related Work
- Autonomous Front Delineation and Tracking Algorithms
- Field Program
  - Underwater Assets
  - Results
- Conclusion and Future Work

## Tracking Ocean Fronts

- Motivation: Improve science data using near real time data processing and ocean models
- Traditional methods use fixed transects with humans-in-the-loop
- Ocean front is the boundary between two distinct bodies of water
- Repeated transects across an ocean front
- Temperature is shown however any water property can be used

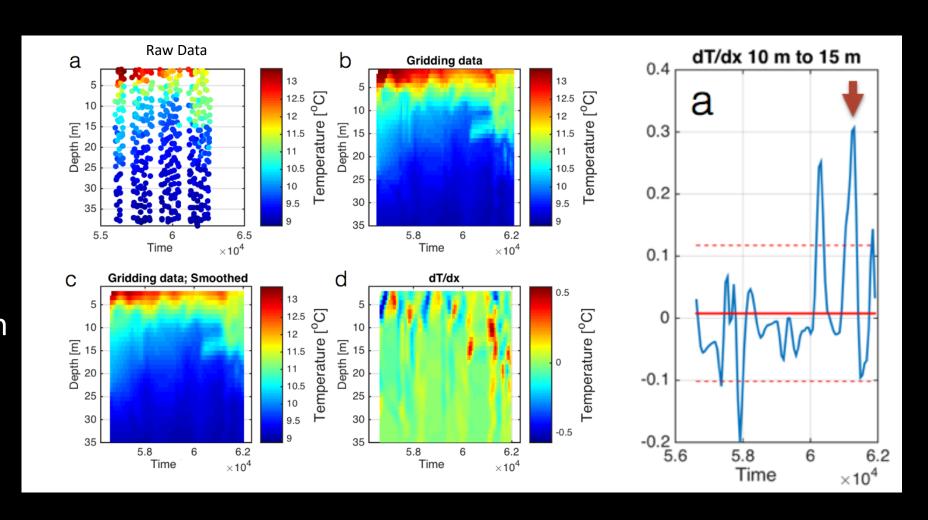


### Related Work

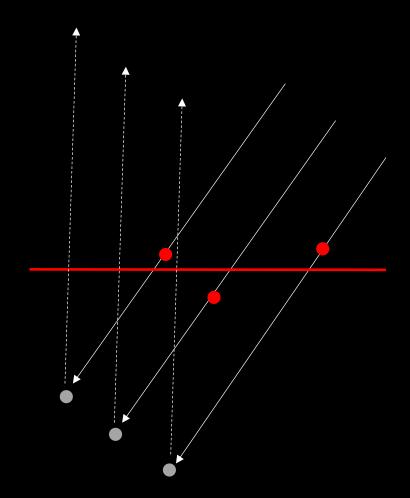
- Cruz, N. A., and Matos, A. C. 2014. Autonomous tracking of a horizontal boundary. In Oceans-St. John's, 2014, 1-6. IEEE.
- Curtin, T. B.; Bellingham, J. G.; Catipovic, J.; and Webb, D. 1993. Autonomous oceanographic sampling networks. Oceanography 6(3):86-94.
- Flexas, M. M.; Troesch, M. I.; Chien, S.; Thompson, A. F.; Chu, S.; Branch, A.; Farrara, J. D.; and Chao, Y. 2018. Autonomous sampling of ocean submesoscale fronts with ocean gliders and numerical model forecasting. Journal of Atmospheric and Oceanic Technology 35(3):503-521.
- Leonard, N. E.; Paley, D. A.; Davis, R. E.; Fratantoni, D. M.; Lekien, F.; and Zhang, F. 2010. Coordinated control of an underwater glider fleet in an adaptive ocean sampling field experiment in monterey bay. Journal of Field Robotics 27(6):718-740.
- Zhang, Y.; Bellingham, J. G.; Ryan, J. P.; Kieft, B.; and Stanway, M. J. 2016. Autonomous four-dimensional mapping and tracking of a coastal upwelling front by an autonomous underwater vehicle. Journal of Field Robotics 33(1):67-81.

### Lateral Gradient Front Detection

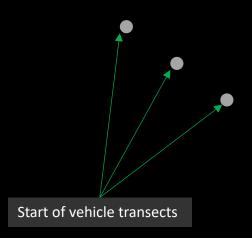
- Detect a change in water property over a transect
- Grid, smooth, and differentiate transect data
- Sum data over specified depth
- Declare front when over threshold value
- Select front from declared fronts



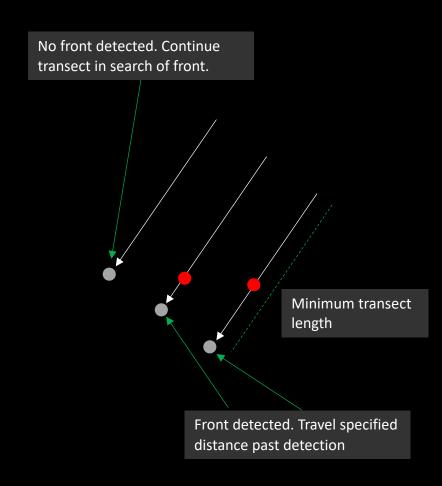
- Given multiple vehicles in near parallel transects
- Estimate a linear front from detections
- Command vehicles on reverse transect, perpendicular to estimated front
- Vehicles may become out of phase, starting subsequent transects at different times



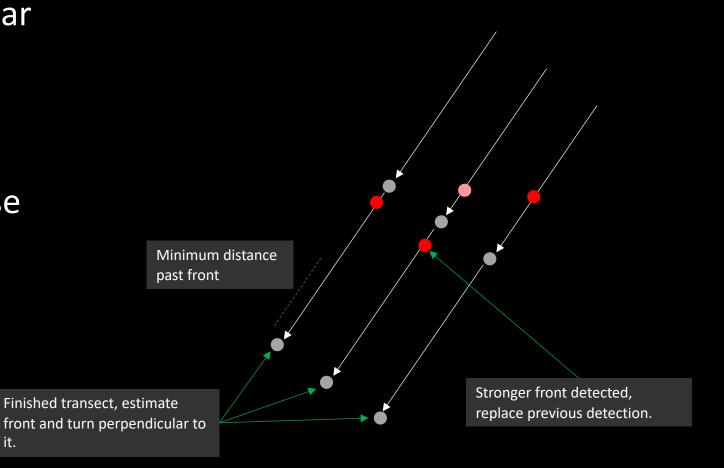
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- Given multiple vehicles in near parallel transects
- Estimate a linear front from detections
- Command vehicles on reverse transect, perpendicular to estimated <u>front</u>
- Vehicles may become out of phase, starting subsequent transects at different times



Estimate front using front

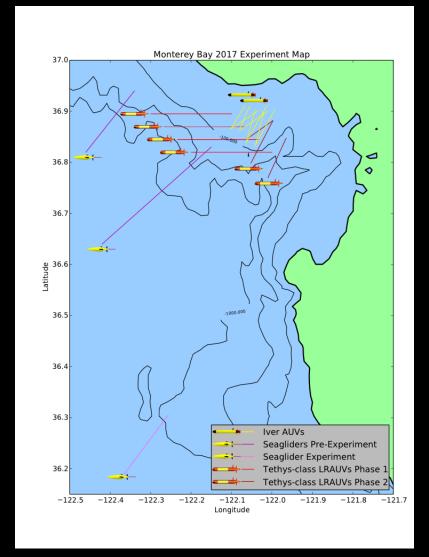
Finished transect, estimate

period

- Given multiple vehicles in near parallel transects
- Estimate a linear front from detections
- Command vehicles on reverse transect, perpendicular to estimated front
- Vehicles may become out of phase, starting subsequent transects at different times

detections from specified time front and turn perpendicular to

# May 2017 Monterey Bay Deployment



### Shana Rae

- Front Detection and Estimation
- High level vehicle control



#### LRAUV (5)

- 1 knot
- Multi-week endurance



#### Iver AUV (2)

- 2-4 knots
- ~12 hour endurance



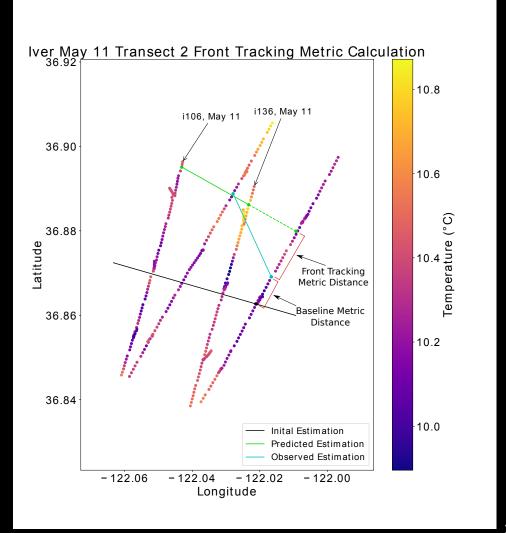
#### Seaglider (1)

- 0.5 knots
- Multi-month endurance



### Front Detection Metric

- Compare front estimation accuracy of fixed transects vs front tracking
- Baseline Metric: Distance between initial front estimation and current front estimation
- Front Tracking Metric: Distance between front estimation N and front estimation N-1

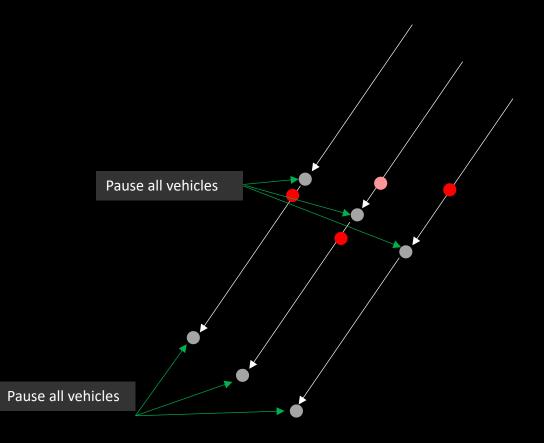


### Iver AUV Algorithm Modifications

 Iver AUVs must remain in close proximity for communication and vehicle safety

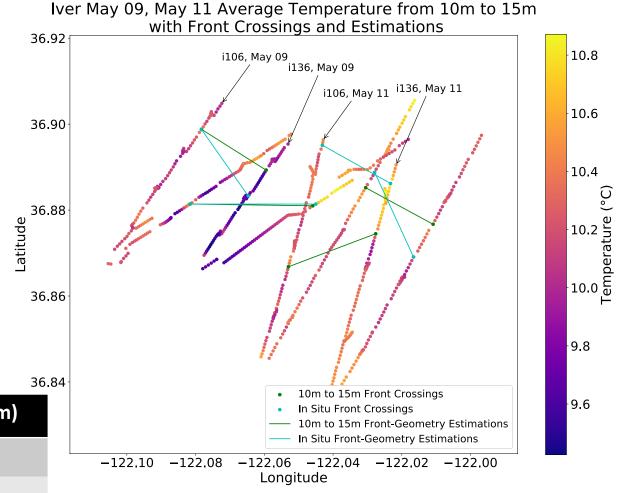
 Pause at each decision point until all vehicles are present

 Every vehicle either continues transect or turns and starts next transect



### Iver AUV Experiment

- Minimum transect distance set to 2.5 km past previous estimated front
- If no front was detected in initial transect, continue 2 km
- Vehicles set to turn around immediately after a front is detected



 Baseline Metric (m)
 Front Tracking Metric (m)

 Average
 1619.598
 839.393

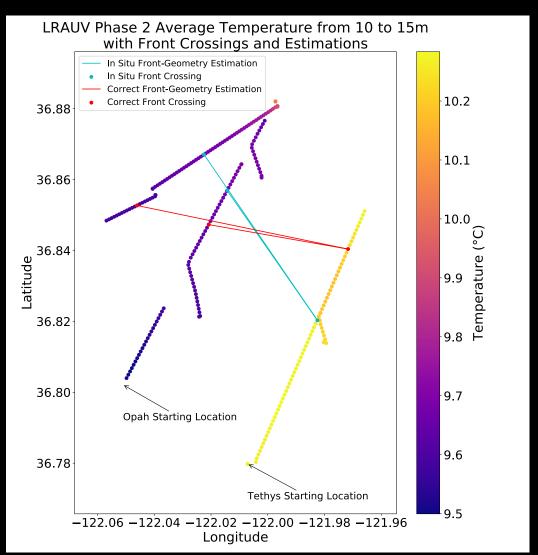
 Std Dev
 943.674
 523.301

## Long-Range AUV Experiment

 Minimum transect distance set to 4.5 km past previous estimated front

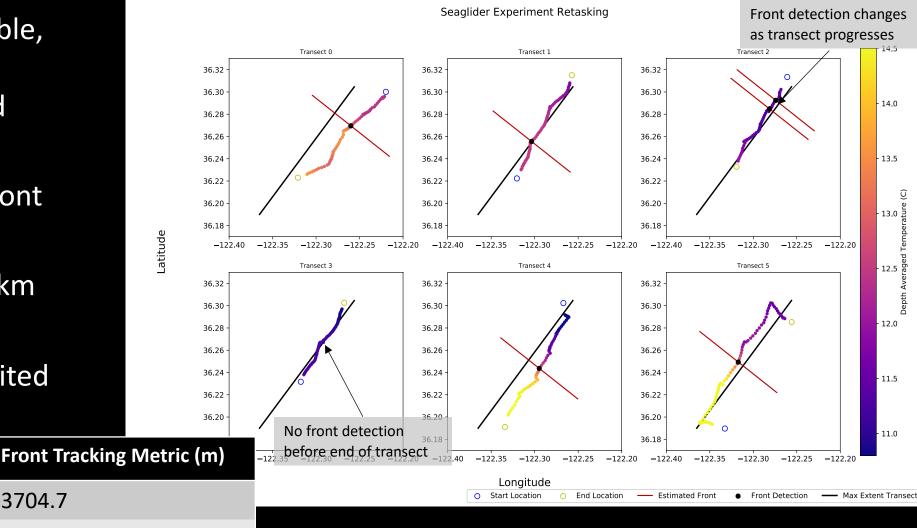
 Vehicles set to turn around immediately after a front is detected

• Software error led to incorrect front estimations



Seaglider Experiment

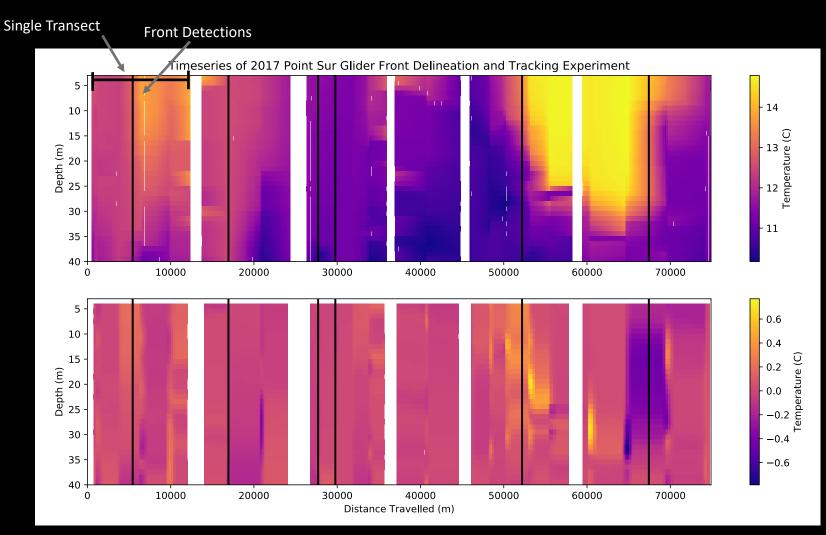
- Single vehicle is available, so a fixed front orientation is assumed
- Minimum transect distance set to 5 km front start of transect
- Distance past front: 5 km
- Short distance parameters due to limited testing timeframe



**Baseline Metric (m)** 

# Seaglider Experiment

- Single vehicle is available, so a fixed front orientation is assumed
- Minimum transect distance set to 5 km front start of transect
- Distance past front: 5 km
- Short distance parameters due to limited testing timeframe



### Conclusion

 Develop method for autonomous tracking of ocean fronts using multiple vehicles

 Demonstrated a proof of concept in Monterey Bay, CA with two Iver AUVS, tow LRAUVs, and a Seaglider

 Introduced a quantitative metric to evaluate the performance of front tracking algorithms

### Future Work

- More deployments and testing
  - Direct comparison between fixed transects and front tracking
- Adding the capabilities to distinguish between fronts
  - Warm-to-Cold vs. Cold-to-Warm
  - Sharp vs. gradual
- Onboard implementation of front tracking
- Non-linear front model [Cruz and Matos, 2014]
- Incorporation of ocean circulation model into operations
- Coordination across vehicle types, including surface vehicles (e.g. wavegliders)

